

Physics with Beta-Beam

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Abstract. A Beta-beam would be a high intensity source of pure ν_e and/or $\bar{\nu}_e$ flux with known spectrum, ideal for precision measurements. Myriad of possible set-ups with suitable choices of baselines, detectors and the beta-beam neutrino source with desired energies have been put forth in the literature. In this talk we present a comparative discussion of the physics reach of a few such experimental set-ups.

Keywords: Magic Baseline, Beta Beam, CERN-INO, Golden Channel, Matter Effect

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INTRODUCTION

Neutrino physics is now poised to move into the precision regime. A number of high-precision neutrino oscillation experiments have been contrived to shed light on the third mixing angle θ_{13} , the sign² of $\Delta m_{31}^2 \equiv m_3^2 - m_1^2$ ($\text{sgn}(\Delta m_{31}^2)$) and the CP phase (δ_{CP}), key missing ingredients of the neutrino mass matrix. The $\nu_e \rightarrow \nu_\mu$ transition probability ($P_{e\mu}$) depends on all these three parameters and is termed the “golden channel” [1, 2] for long baseline accelerator based experiments³. In order to exploit this channel, we need a pure and intense ν_e (or $\bar{\nu}_e$) beam at the source. The beta-beam serves this purpose. In this talk, we will focus on a few proposed experimental scenarios dealing with beta-beam and discuss the consensus direction for the future.

BETA-BEAM

Zucchelli [4] put forward the novel idea of beta-beam [3, 4, 5, 6, 7, 8, 9, 10, 11, 12], which is based on the concept of creating a pure, well-known, intense, collimated beam of ν_e or $\bar{\nu}_e$ through the beta decay of completely ionized radioactive ions. It will be achieved by producing, collecting, and accelerating these ions and then storing them in a ring [13]. Feasibility of this proposal and its physics potential is being studied in depth [14], and will take full advantage of the existing accelerator complex and CERN and FNAL. It has been proposed to produce

ν_e beams through the decay of highly accelerated ^{18}Ne ions and $\bar{\nu}_e$ from ^6He [4, 13]. More recently, ^8B and ^8Li [15] with much larger end-point energy have been suggested as alternate sources since these ions can yield higher energy ν_e and $\bar{\nu}_e$ respectively, with lower values of the Lorentz boost γ [10, 11, 16]. It may be possible to store radioactive ions producing beams with both polarities in the same ring. This will enable running the experiment in the ν_e and $\bar{\nu}_e$ modes simultaneously. Details of the four beta-beam candidate ions can be found in Table 1 of [9].

THE “GOLDEN CHANNEL” ($\nu_e \rightarrow \nu_\mu$)

The expression for $P_{e\mu}$ in matter, upto second order in the small parameters $\alpha \equiv \Delta m_{21}^2 / \Delta m_{31}^2$ and θ_{13} , is [1, 2]:

$$\begin{aligned}
 P_{e\mu} \simeq & \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \\
 & + \alpha \sin 2\theta_{13} \xi \sin \delta_{CP} \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
 & + \alpha \sin 2\theta_{13} \xi \cos \delta_{CP} \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
 & + \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}; \quad (1)
 \end{aligned}$$

where $\Delta \equiv \Delta m_{31}^2 L / (4E)$, $\xi \equiv \sin 2\theta_{12} \sin 2\theta_{23}$, and $\hat{A} \equiv \pm(2\sqrt{2}G_F n_e E) / \Delta m_{31}^2$. G_F and n_e are the Fermi coupling constant and the electron density in matter, respectively. The sign of \hat{A} is positive (negative) for neutrinos (anti-neutrinos) with NH and it is opposite for IH. While the simultaneous dependence of this oscillation channel on θ_{13} , $\text{sgn}(\Delta m_{31}^2)$ and δ_{CP} allows for the simultaneous measurement of all these three quantities, it also brings in the problem of “parameter degeneracies” – the θ_{13} - δ_{CP} intrinsic degeneracy [17], the $\text{sgn}(\Delta m_{31}^2)$ degeneracy [18] and the octant of θ_{23} degeneracy [19] – leading to

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² The neutrino mass hierarchy is termed “normal (NH)” (“inverted (IH)”) if $\Delta m_{31}^2 = m_3^2 - m_1^2$ is positive (negative).

³ The ν_e survival probability can also be used to cleanly measure θ_{13} and $\text{sgn}(\Delta m_{31}^2)$ [3].

an overall eight-fold degeneracy in the parameter values [20]. The degeneracies, unless tackled, always reduce the sensitivity of the experiment.

THE CERN-INO MAGICAL SET-UP

Interestingly, when $\sin(\hat{A}\Delta) = 0$, the last three terms in Eq. (1) drop out and the δ_{CP} dependence disappears from the $P_{e\mu}$ channel. The problem of clone solutions due to the first two types of degeneracies are therefore evaded. Since $\hat{A}\Delta = \pm(2\sqrt{2}G_F n_e L)/4$ by definition, the first non-trivial solution for $\sin(\hat{A}\Delta) = 0$ reduces to $\rho L = \sqrt{2}\pi/G_F Y_e$, where Y_e is the electron fraction inside earth. This gives $\frac{\rho}{[\text{g/cc}]} \frac{L}{[\text{km}]} \simeq 32725$, which for the PREM [21] density profile of the earth is satisfied for the “magic baseline” [20, 22, 23], $L_{\text{magic}} \simeq 7690$ km. At this baseline the sensitivity to the mass hierarchy and θ_{13} is quite significant [22], while the sensitivity to δ_{CP} is absent.

The large baseline also entails traversal of neutrinos through denser regions of the earth, capturing near-maximal matter contribution to the oscillation probability. In fact, for this baseline, the average earth matter density calculated using the PREM profile is $\rho_{av} = 4.25$ g/cc, for which the resonance energy

$$\begin{aligned} E_{res} &\equiv \frac{|\Delta m_{31}^2| \cos 2\theta_{13}}{2\sqrt{2}G_F N_e} \\ &= 7 \text{ GeV}, \end{aligned} \quad (2)$$

for $|\Delta m_{31}^2| = 2.4 \times 10^{-3} \text{ eV}^2$ and $\sin^2 2\theta_{13} = 0.1$. Of course neutrino oscillation probability for long baseline experiments depend on the product of the mixing term and the mass squared difference driven oscillatory term inside matter. Largest flavor conversions are possible when both these terms are large [3, 24]. The exact neutrino transition probability $P_{e\mu}$ using the PREM density profile is given in Fig. 1 which has been taken from [9]. For neutrinos (antineutrinos), matter effects for the longer baselines bring a significant enhancement of $P_{e\mu}$ for NH (IH), while for IH (NH), the probability is almost unaffected. This feature can be used to determine the neutrino mass hierarchy (see left panel of Fig. 1). For $L = 7500$ km, which is close to the magic baseline, the effect of the CP phase is seen to be almost negligible. This allows a clean measurement of $\text{sgn}(\Delta m_{31}^2)$ and θ_{13} (see right panel of Fig. 1), while for all other cases the impact of δ_{CP} on $P_{e\mu}$ is appreciable.

A large magnetized iron calorimeter (ICAL) is all set to come up at the India-based Neutrino Observatory (INO) [25]. ICAL@INO will be a 50 kton detector, capable of detecting muons along with their charge, with good energy and angular resolution. It might be upgraded to 100 kton. If a beta-beam facility is built at CERN, ICAL@INO could serve as an excellent far detector for

observing the oscillated ν_μ . The USP of this experimental set-up would be the CERN-INO distance, which corresponds to 7152 km, tantalizingly close to the magic baseline. This would enable an almost degeneracy-free measurement of $\text{sgn}(\Delta m_{31}^2)$ and θ_{13} as discussed above. In addition, one could exploit the near-maximal matter effects by tuning the beam energy to be close to 6-7 GeV (see Fig. 1).

We consider ${}^8\text{B}$ (${}^8\text{Li}$) [15] ion as a possible source for a ν_e ($\bar{\nu}_e$) beta-beam and show the expected flux for our experimental set-up in the left panel of Fig. 2. For the Lorentz boost factor $\gamma = 250 - 650$ the ${}^8\text{B}$ and ${}^8\text{Li}$ sources have peak energy around $\sim 4 - 9$ GeV. We assume 2.9×10^{18} useful decays per year for ${}^8\text{Li}$ and 1.1×10^{18} for ${}^8\text{B}$, for all values of γ . The expected number of events are shown in the right panel of Fig. 2. We take a detector energy threshold of 1.5 GeV, detection efficiency of 80% and charge identification efficiency of 95%. For discussion on our backgrounds and details of our statistical analysis we refer the readers to [9, 12].

We define the $\sin^2 2\theta_{13}$ sensitivity reach of the CERN-INO beta-beam experiment as the upper limit on $\sin^2 2\theta_{13}$ that can be put at the 3σ C.L., in case no signal for θ_{13} driven oscillations is observed and the data is consistent with the null hypothesis. At 3σ , the CERN-INO β -beam set-up can constrain $\sin^2 2\theta_{13} < 1.14 \times 10^{-3}$ with five years of running of the beta-beam in both polarities with the same $\gamma = 650$ and full spectral information. The $\sin^2 2\theta_{13}(\text{true})$ discovery reach is defined as the minimum value of $\sin^2 2\theta_{13}(\text{true})$ for which we can distinguish the signal at the 3σ C.L. We present our results in the left panel of Fig. 3, as a function of γ . The plot presented show the most conservative numbers which have been obtained by considering all values of $\delta_{CP}(\text{true})$ and both hierarchies. We refer the reader to [12] for details. The hierarchy sensitivity is defined as the minimum value of $\sin^2 2\theta_{13}(\text{true})$, for which one can rule out the wrong hierarchy at 3σ C.L. The results are depicted as a function of γ in the right panel of Fig. 3. For NH true, the $\text{sgn}(\Delta m_{31}^2)$ reach corresponds to $\sin^2 2\theta_{13}(\text{true}) > 5.51 \times 10^{-4}$, with 5 years energy binned data of both polarities and $\gamma = 650$. Here we had assumed $\delta_{CP}(\text{true}) = 0$. However, as discussed before, the effect of δ_{CP} is minimal close to the magic baseline and hence we expect this sensitivity to be almost independent of $\delta_{CP}(\text{true})$ (see [12] for details).

THE CERN-MEMPHYS PROJECT

The CERN-MEMPHYS proposal comprises of sending a low gamma beta-beam from CERN to the envisaged MEMPHYS, which would be a 440 kton fiducial mass water detector located in Fréjus, at a distance of 130 km

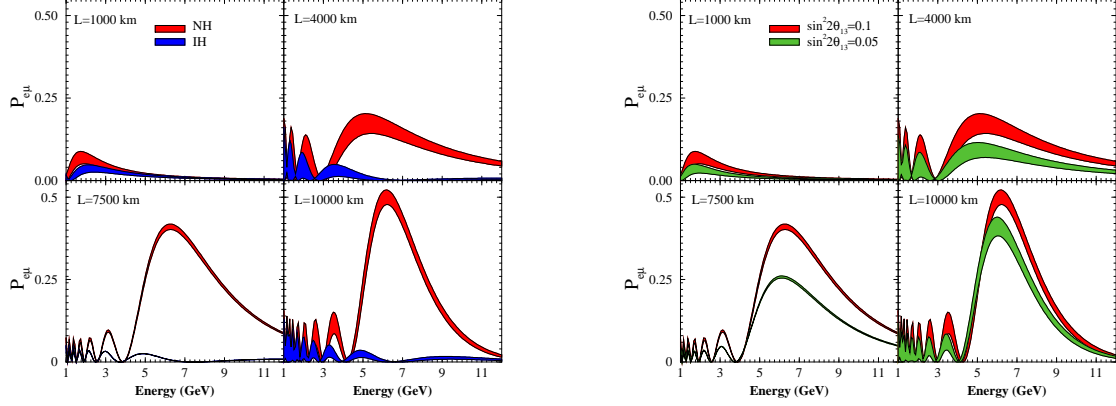


FIGURE 1. Both the panels show the energy dependence of $P_{e\mu}$ for four baselines where the band reflects the effect of the unknown δ_{CP} . Left panel clearly depicts the effect of δ_{CP} in making distinction between normal (NH) & inverted (IH) hierarchy with $\sin^2 2\theta_{13} = 0.1$. Right panel reflects the difference in $P_{e\mu}$ for two different values of $\sin^2 2\theta_{13}$ with NH.

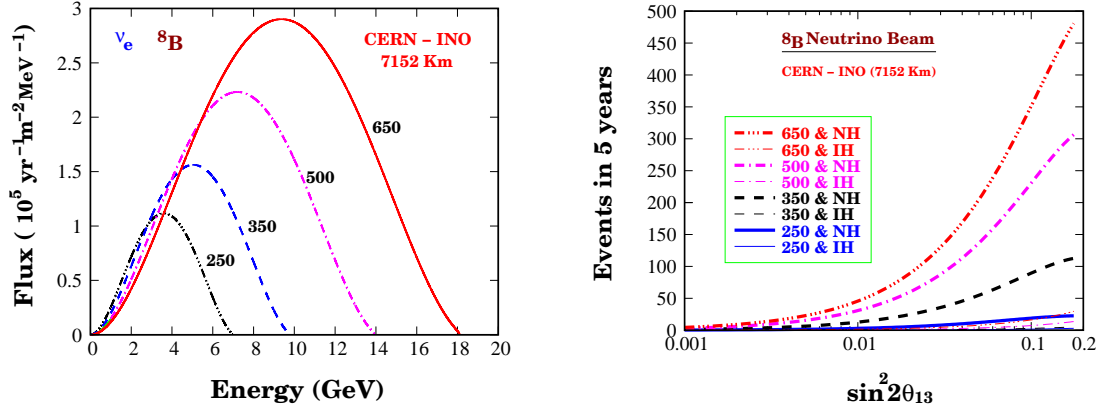


FIGURE 2. Left panel shows the boosted unoscillated spectrum of neutrinos from ${}^8\text{B}$ ion which will hit the INO detector, for four different benchmark values of γ . The expected number of μ^- events in 5 years running time with 80% detection efficiency as a function of $\sin^2 2\theta_{13}$ are presented in right panel. The value of γ and the hierarchy chosen corresponding to each curve is shown in the figure legend.

from CERN. The major advantage of this set-up is that one needs very reasonable values of the Lorentz Boost $\gamma = 100$ and ${}^{18}\text{Ne}$ and ${}^6\text{He}$ ions for producing the beta-beam. The current accelerator capabilities at CERN are expected to be enough for producing a beta-beam with $\gamma = 100$ without requiring any upgrades and affecting the running of LHC. The band between the red solid lines in Fig. 4 show the 3σ “discovery reach” for $\sin^2 2\theta_{13}(\text{true})$ using the combined 5 years run in ν_e and $\bar{\nu}_e$ polarities. The band corresponds to changing the systematic errors from 2% to 5%. The 3σ $\sin^2 2\theta_{13}(\text{true})$ discovery reach is defined as the minimum value of $\sin^2 2\theta_{13}(\text{true})$ which could produce a 3σ unambiguous signal at the detector. The strongest point of this experiment is its tremendous sensitivity to CP violation. Maximal CP violation can be observed at the 3σ C.L. if $\sin^2 2\theta_{13}(\text{true}) > 2 \times 10^{-4}$. Another major advantage of this set-up is that if the SPL

is built at CERN, then it could serve as a superbeam experiment as well. In that case, one could run could combine simultaneous 5 years of running of ν_e beta-beam with 5 years of running of the SPL superbeam, without having to run the experiment in the $\bar{\nu}_e$ mode.

COMPARING DIFFERENT SET-UPS

The authors of [5] studied the physics potential of beta-beams, using ${}^{18}\text{Ne}$ and ${}^6\text{He}$ as the source ions and allowing for different values of γ and L . Table 1 describes the details of the three illustrative set-ups analyzed in details in [5]. Fig. 5 shows the $\sin^2 2\theta_{13}$ sensitivity reach of these three set-ups and compares them with the corresponding potential of that expected from two standard neutrino factory set-ups. We note that the sensitivity of

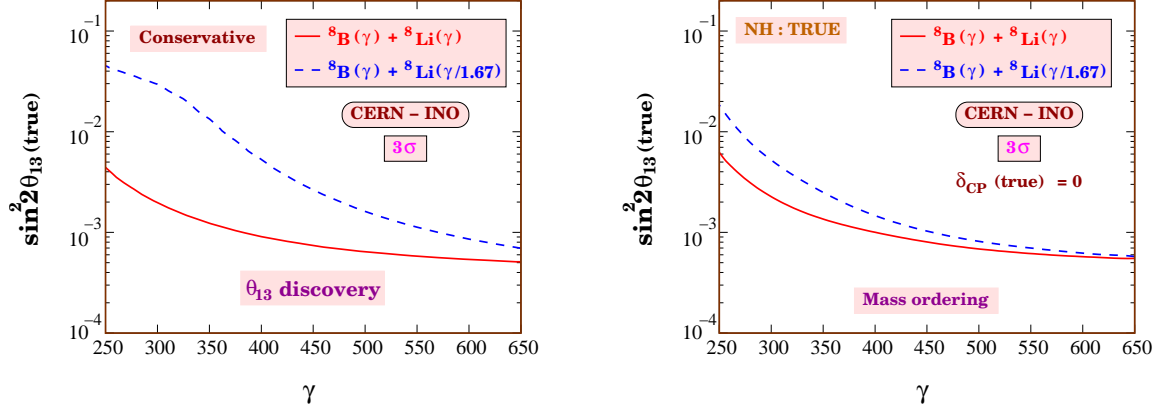


FIGURE 3. Left panel shows the 3σ discovery reach for $\sin^2 2\theta_{13}(\text{true})$. Right panel shows the minimum value of $\sin^2 2\theta_{13}(\text{true})$ for which the wrong inverted hierarchy can be ruled out at the 3σ C.L., as a function of the Lorentz boost γ . The red solid lines in both the panels are obtained when the γ is assumed to be the same for both the neutrino and the antineutrino beams. The blue dashed lines show the corresponding limits when the γ for the ${}^8\text{Li}$ is scaled down by a factor of 1.67 with respect to the γ of the neutrino beam, which is plotted in the x -axis.

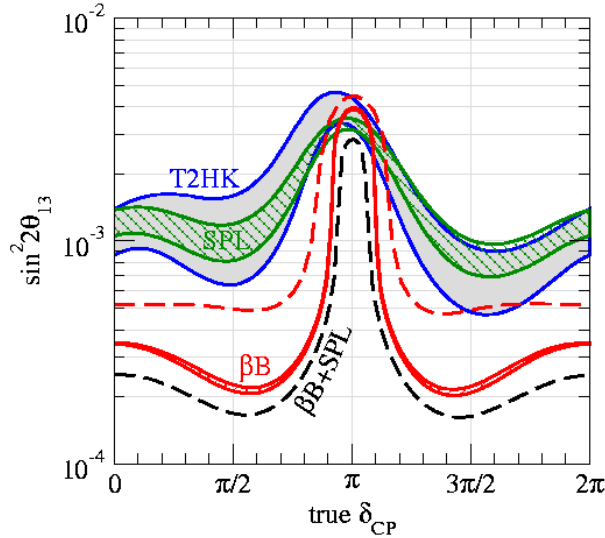


FIGURE 4. 3σ discovery reach for $\sin^2 2\theta_{13}(\text{true})$ for β -beam, Super Beam and T2HK (phase II of the T2K experiment) as a function of $\delta_{CP}(\text{true})$. The running time is $(5\nu + 5\bar{\nu})$ year for β -beam with twice the standard luminosity and $(2\nu + 8\bar{\nu})$ years for the Super Beams (4 MW).

the CERN-INO beta-beam experiment is better than that quoted for the set-up 2 of Table 1. The set-up 3 is better, but it needs $\gamma = 1000$. While none of these three set-ups are competitive with the neutrino factory at magic baseline or the CERN-INO beta-beam set-up as far as the hierarchy sensitivity is concerned, the CP sensitivity of the three set-ups is extremely good. For CP studies the performance of beta-beam is comparable with neutrino factory at $L = 3000 - 4000$ km.

In Table 2 we present a quantitative comparison of

TABLE 1. The number of signal/background events for different combinations of the chosen detector type and values of γ . WC stands for Water Cherenkov, while TASD means a Totally Active Scintillator Detector.

Set-up	1	2	3
Detector type	WC	TASD	TASD
m [kt]	500	50	50
γ	200	500	1000
L [km]	520	650	1000
ν signal	1983	2807	7416
ν background	105	31	95

the potential of the different set-ups. The first two rows of the table shows the sensitivity reach of the the neutrino factory experiments at 3000 km and 7500 km respectively. The third and fourth rows show the physics reach of the CERN-INO and CERN-MEMPHYS beta-beam proposal. The remaining entries have been taken from various papers on beta-beam and their arXiv numbers are mentioned in the first column of the Table. The second column shows the γ value considered, the third column gives the L taken, fourth column the type of detector considered⁴, while the fifth column shows the time of running of the experiment in the neutrino (T_{ν_e}) and antineutrino ($T_{\bar{\nu}_e}$) modes. The cases shown as 10(S) correspond to *simultaneous* running of the ν_e and $\bar{\nu}_e$ beams for a period of 10 years, with the γ corresponding to the $\bar{\nu}_e$ beam suppressed by a factor of 1.67. The last three

⁴ The detector type (MI) stands for magnetized iron.

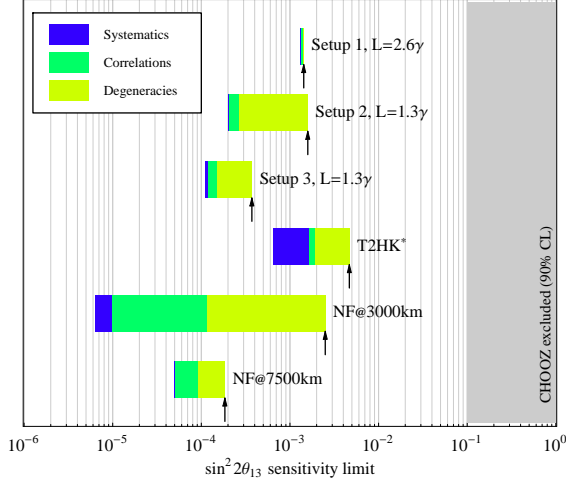


FIGURE 5. The $\sin^2 2\theta_{13}$ sensitivity limits for the different setups and other representatives. Here $n = 0$ (decays per year fixed) and the 3σ confidence level are chosen. The final sensitivity limits are obtained as the right edges of the bars after successively switching on systematics, correlations, and degeneracies.

TABLE 2. Comparison between the different experimental set-ups. See the text for details.

γ	L(km)	Detector	T_p/T_ν	$\sin^2 2\theta_{13}$	$\text{sgn}(\Delta m_{21}^2)$	Max CPV
NF@3000	3000	50 (MI)	4/4	1.5×10^{-3}	1.0×10^{-2}	7×10^{-5}
NF@7500	7500	50 (MI)	4/4	2×10^{-4}	2×10^{-4}	No sens
CERN-INO	350	7152	50 (MI)	5/5	1.2×10^{-3}	1.3×10^{-3}
	650	7152	50 (MI)	5/5	5.1×10^{-4}	5.6×10^{-4}
CERN-MEMPHYS	100/100	130	440 (WC)	10/10	5×10^{-3}	2.5×10^{-3}
					+SPL+ATM	2×10^{-4}
hep-ph/0506237	200/200	520	500 (WC)	8/8	1.5×10^{-3}	2×10^{-2}
	500/500	650	50 (TASD)	8/8	3.2×10^{-4}	4.5×10^{-2}
	1000/1000	1300	50 (TASD)	8/8	1.2×10^{-4}	7×10^{-5}
hep-ph/0312068	100/60	130	400 (WC)	10(S)	Not	No Sens
	580/350	732	400 (WC)	10(S)	Given	$[2 \times 10^{-2}]$
	2500/1500	3000	40 (MI)	10(S)		$[4 \times 10^{-3}]$
hep-ph/0503021	120/120	130	440 (WC)	10(S)	$[5 \times 10^{-3}]$	Not
	150/150	300	440 (WC)	10(S)	$[6 \times 10^{-4}]$	Given
	350/350	730	440 (WC)	10(S)	$[4 \times 10^{-4}]$	$[1 \times 10^{-4}]$

columns show the (approximate) 3σ θ_{13} discovery (or sensitivity reach), the hierarchy sensitivity and CP sensitivity respectively. The entries in square brackets correspond to 99% C.L. sensitivity. The results correspond to assumed true normal hierarchy. Since the θ_{13} and hierarchy reach of the experiment in general depends on $\delta_{CP}(\text{true})$, we give the most conservative value. Note that for the CERN-MEMPHYS project the hierarchy sensitivity comes mainly from adding the atmospheric neutrino data in the megaton MEMPHYS detector.

CONCLUSIONS

In this talk, we discussed the expected physics reach of selected experimental set-ups using a beat-beam. Beta-beams are seen to have extremely good physics reach which are comparable to those expected in neutrino factories.

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